Snow Depth as an Indicator of Weather and Climate in the Sierra Nevada

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Abstract: Snow is an important determinant of the magnitude and timing of streamflow in the mountains of western North America. Two different measures exist over long historical periods (more than 3 decades): snowcourse surveys and cooperative weather records. Snowcourses monitor the snow depth and snow water content at mid to high elevations at a one time per month interval. Daily cooperative precipitation and snow records provide event-scale information of snow depth and liquid equivalent precipitation, with most stations confined to low and mid level elevations. The purpose of this study is to determine: (1) whether the cooperative station snow depth contains useful weather and climate information, (2) how cooperative snow depth variability is related to snowcourse variability, and (3) how it is related to other weather elements.

From an examination of stations in the Sierra Nevada of California, it is clear that cooperative snow records and snowcourse records have consistent spatial and temporal variability. For over 40 years of record, there is a strong correlation between the two methods of measuring snow. Both measures show strong spatial coherence of monthly snow anomalies between the central and southern Sierra Nevada. The cooperative snow depth provides insight into snowstorms. Event-scale snow density is derived by combining snow depth (SD) with liquid equivalent precipitation (Ppt).

We show that high snow ratio (low density snow or high SD/Ppt) events have low temperatures and high amplitude atmospheric circulation patterns over the eastern North Pacific. In contrast, low snow ratio (high density or low SD/Ppt) events have warm temperatures and a zonal flow pattern with a southerly displaced storm track from Hawaii to the West Coast.

Introduction

There is significant variation in annual and seasonal streamflow in the mountains of the western United States. In the Sierra Nevada of California, the magnitude of annual runoff is closely linked to the magnitude of annual precipitation, but the timing of runoff depends more on temperature and the condition of the snowpack than on when precipitation occurs (Kahrl 1979; Aguado *et al* 1991). This linkage is evident in the lag between precipitation (with a January-February maximum) and streamflow (with a March-May maximum, depending on elevation).

The peak in human consumptive water use (April-July) more nearly coincides with the streamflow maximum than with the precipitation maximum (Roos 1989). Because of this, the water supply in the western United States relies heavily on snowpack for water storage. However, about half of the Sierra Nevada snowpack accumulation areas are in basins that are extremely sensitive to temperature (Roos 1989). If climate change were to increase the mean annual temperature, this could cause earlier runoff and decreased spring snowpack (Gleick 1987; Lettenmaier

In K.T. Redmond, Editor, 1992. Proceedings of the Eighth Annual Pacific Climate (PACLIM) Workshop, March 10-13, 1991: California Department of Water Resources, Interagency Ecological Studies Program Technical Report 31.

and Gan 1990). Our long-term goal is to better understand weather and climate influences on snow and the role snow plays in controlling streamflow variation.

This study is an initial look at the variability of snow in the central and southern Sierra Nevada. A companion study (Cayan *et al* this volume) focuses on the variability of snowcourse water content in the West. In so doing, we want to evaluate the cooperative snow data as a meteorological/climatological indicator. Furthermore, we want to begin to exploit the information it provides on interannual variability of winter storms and snow in the Sierra Nevada. To accomplish this, we examine daily and monthly snow accumulation and liquid water equivalents at two cooperative weather stations and two high elevation snowcourses. We then relate these snow parameters to broad-scale atmospheric circulation, temperature, and precipitation. We accomplish this using three steps:

- Correlate the monthly and seasonal snow measurements.
- Examine the spatial coherence of the two snow measures.
- Examine the difference between high ratio (high snow depth to liquid equivalent precipitation or "dry") snow versus low ratio (low snow depth to liquid equivalent or "wet") snowstorm episodes.

A recent examination of streamflow variability (Riddle, Cayan, and Aguado 1990) has demonstrated the importance of temperature in determining whether precipitation produces runoff or is stored in the snowpack. Linear models developed in that study show seasonal mean precipitation and temperature can explain a large portion of seasonal streamflow in low, moderate, and high elevation basins in central and northern California. In general, these models explain over 60% of seasonal streamflow variation in the moderate and high basins. Nearly 80% of the independent period variation was explained in the highest basins during the heavy runoff, late spring period. The importance of snow in the timing of runoff was emphasized by the dependence of predictor relationships on mean elevation of the watersheds.

Climate is one decisive factor in determining the quantity and character of streamflow (Bruce and Clark 1966); another is basin elevation (Cayan and Peterson 1989). Since there is a strong link between both climate and elevation and snowpack formation, an understanding of the variability of snow water content would contribute to our understanding of climate's role. A better understanding of that role would be beneficial in optimizing water management decisions.

The Study Region and Climatic Data

The study area is the Sierra Nevada from the upper San Joaquin River basin in the southern Sierra near Fresno, California, northward to the Yuba River basin near Marysville, California (Figure 1). From this region,

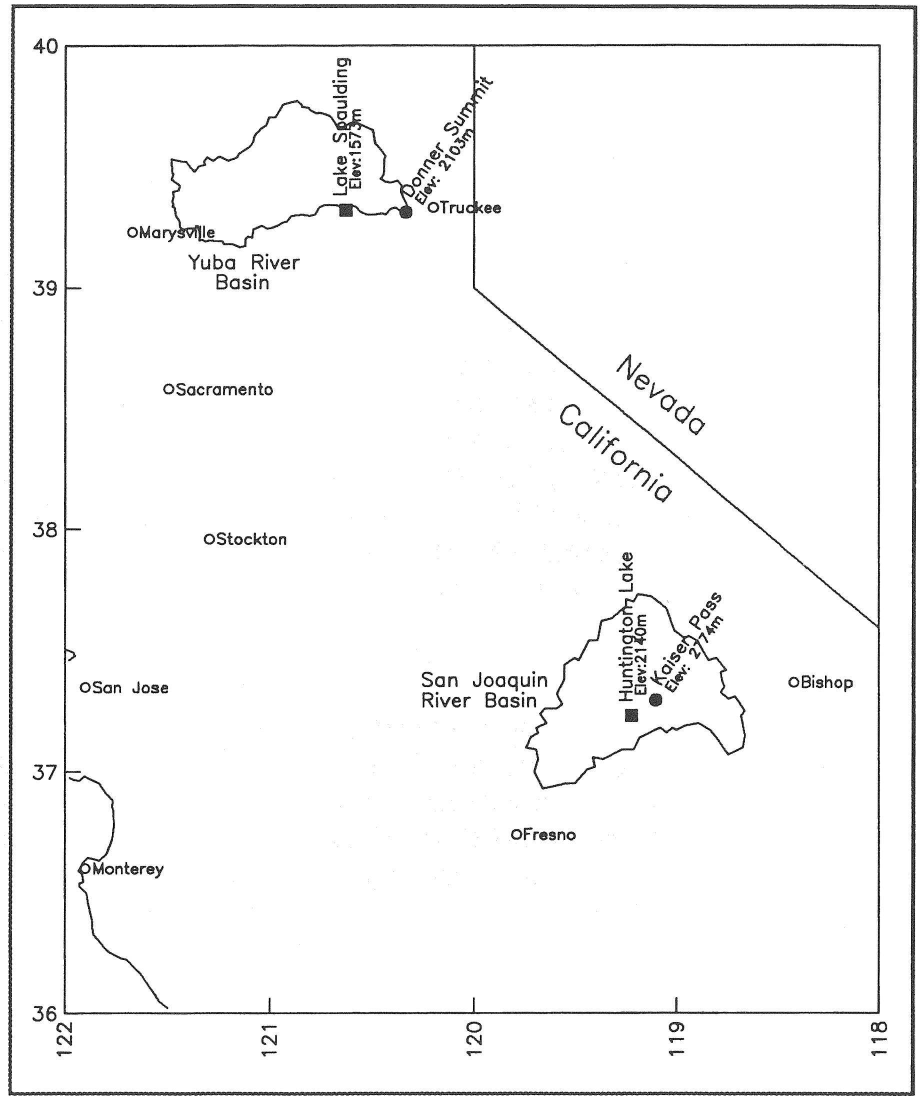


Figure 1. Map showing the cooperative observing stations (closed squares) and snowcourses (closed circles) used in this study. Distance from Donner Summit to Kaiser Pass is about 250 kilometers.

we selected snow observations from two river basins for study. The Yuba River watershed (mean elevation in the 1000- to 2000-meter range) and the upper San Joaquin watershed (mean elevation above 2000 meters), represent moderate and high elevation basins.

There are four primary methods of measuring snow in the Sierra Nevada: snowcourses, aerial markers, snow sensors, and cooperative weather observers. The most familiar method for climate researchers is the snowcourse survey. Snowcourses provide highly accurate measures of snow depth and snow water content at mid to high elevations. Some Sierra Nevada snowcourse records begin as early as 1910, but most of the long-term courses were first surveyed in the 1940s. The primary disadvantages of snowcourse surveys are the coarse temporal resolution and shortage of mid and low elevation data. Snowcourses are usually surveyed, at most, from four to six times each winter. Some are only surveyed once or twice a year. Most snowcourses are above 2000 meters, some are over 3000 meters, but few are below 1500 meters. There were about 400 snowcourses in California, but surveys have been discontinued at over 90 of these (DWR 1991).

Aerial snow depth markers are co-located with over 100 of the snowcourses to provide water managers a quick look at snow conditions between surveys. Most have about 40 years of record. These markers are pipes fitted with metal vanes, allowing depth measurements to be made photographically from aircraft (DWR 1971). These markers are easier and faster but are not as accurate as snowcourses, and they do not measure water content.

There are over 100 snow sensors in California that measure water content at the sensor's location. Most are co-located with snowcourses and most automatically transmit measurements to central locations. Some also measure precipitation and/or temperature. Most are located above 2000 meters, and all are higher than 1500 meters (DWR 1991). Snow sensor measurements are of limited utility. The majority were installed during the 1970-1980s and have short record lengths. They do not provide snow depth data and there may be accuracy problems.

The most numerous and probably the most under-utilized snow measurement records in California are the cooperative weather observer daily snow depth records from the National Climatic Data Center (NCDC). The EarthInfo, Inc. (distributor for NCDC) CD-ROM contains 1,131 cooperative snow station records for California. Of these, 753 station records begin before 1950 and 26 before 1930; 293 stations have 40 or more years of record. Station elevations run from sea level to over 2500 meters. There are 556 stations with at least 20 years of record and less than 20% missing data: 405 of those were still active in 1989. More than 200 stations are in the temperature-sensitive elevation range:

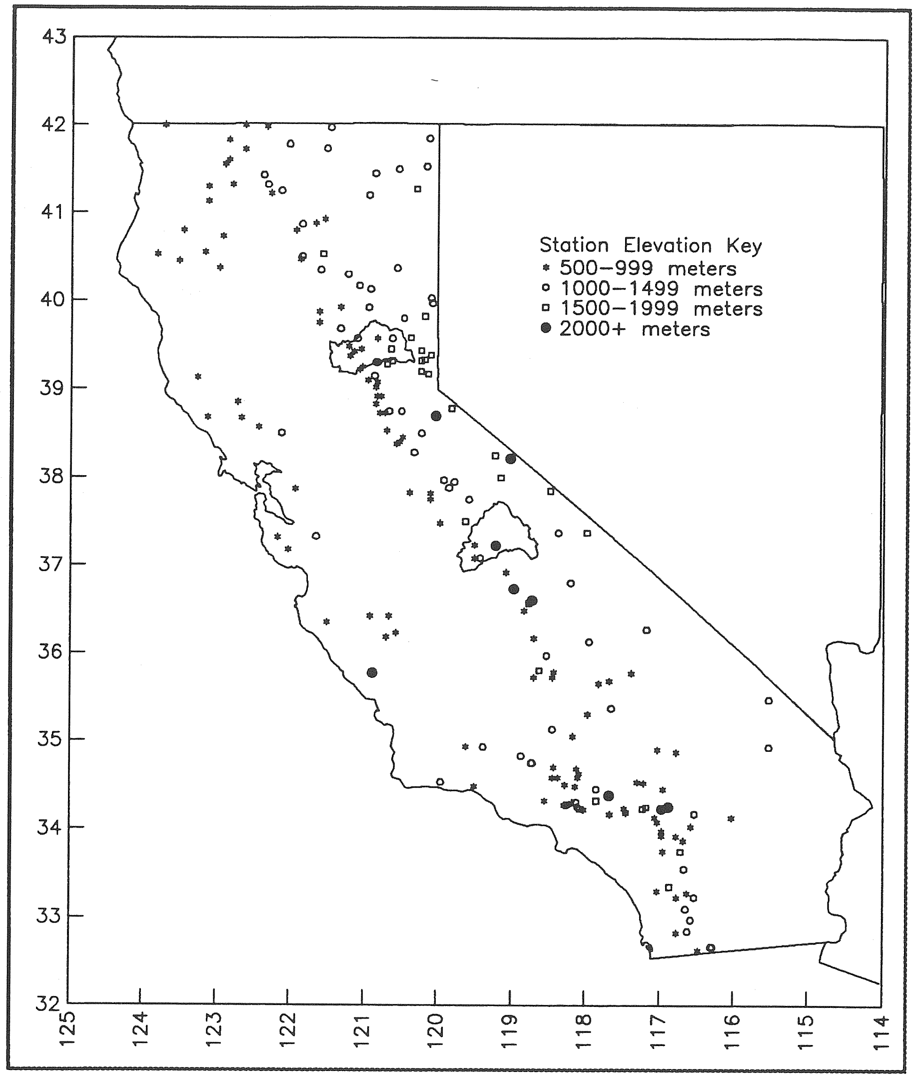
500-999 meters	114
1000-1499 meters	66
1500-1999 meters	28
2000 meters and higher	10

The cooperative snow depth stations are mapped in Figure 2 according to these four elevation categories.

All of the cooperative stations that report snow depth also report daily liquid equivalent precipitation, and most report maximum and minimum temperatures. Beyond the data contained on the CD are many post-World War II records and most of the earliest records, which have not yet been converted to computer-readable form.

Data used in this study are cooperative station weather reports, snowcourse measurements, and upper air heights and temperatures. We do not use snow marker data, because it does not provide any information not available in the snowcourse records, nor snow sensor data, due to the shortness of the records. The cooperative data include daily, monthly, and seasonal precipitation, temperature, and snow accumulation from two weather stations in the Sierra Nevada. The snowcourse water content measurements are from two nearby snowcourses. The upper air data are

Figure 2. Map showing the 218 long record cooperative observing stations in California.



the twice daily 700-mb gridded heights. Temperature anomalies were derived for the sea surface to 700-mb layer from the 700-mb height and sea level pressure (SLP) for the eastern North Pacific and western United States. The 700-mb height, height anomaly, and temperature anomaly data are from the National Meteorological Center (NMC) gridded data set for the Northern Hemisphere, supplied by the NOAA Climate Analysis Center.

Daily precipitation and snow data are from the National Climatic Data Center (NCDC), NOAA via EarthInfo, Inc. *CLIMATEDATA CD-ROM Volume 2.01*, and EarthInfo software. The two cooperative stations are Lake Spaulding (1573 meters) for the Yuba River and Huntington Lake (2140 meters) for the San Joaquin River (Figure 1 and Table 1). In this study we will examine the utility of the cooperative snow depth data for climate research.

The snowcourse data are from California Department of Water Resources Bulletins 129-70 (*Snow Survey Measurements through 1970*) and 120-71 through 120-89 (*Water Conditions in California*). The snowcourses chosen are Donner Summit (Yuba River) and Kaiser Pass (San Joaquin River) (Figure 1 and Table 1). The Donner Summit snowcourse, at 2103 meters, is about 250 km north of and 670 m lower than the Kaiser Pass snowcourse. Donner Summit is about 25 km east of and 530 m higher than Lake Spaulding. Both Donner Summit and Lake Spaulding are on the divide between the American and Yuba River basins, just on the Yuba River side. Kaiser Pass is roughly 13 km northeast of and 630 m higher than Huntington Lake. Both are in the San Joaquin basin.

Table 1
Cooperative Weather Station and Snowcourse Location and Elevation Data
(The cooperative station mean annual liquid equivalent precipitation, snow accumulation, snow ratio [long-term mean snow / long-term mean precipitation], and mean annual average temperature are also given.
The long-term mean April 1st snow water content is listed for both snowcourses.

Station Name	Location			Station Means			
Weather Station	Lat	Lon	Elev	Ppt	Snow	Ratio	µAT
Lake Spaulding	39.32N	120.63W	1573	1806	6624	3.668	8.5
Huntington Lake	37.23N	119.22W	2140	1004	5410	5.388	8.0
Snow Course	Lat	Lon	Elev	April 1st WC			
Donner Summit	39.31N	120.34N	2103	1013			
Kaiser Pass	37.30N	119.10W	2774	970			

Ppt = Mean Annual Precipitation (mm)
Snow = Mean Annual Snow Accumulation (mm)
Ratio = Snow / Ppt
µAT = Mean Annual Air Temperature (C)
WC = Mean April 1st Snow Water Content

Snow Measurement

The two snow measurements studied here are totally different in both method and intent. Cooperative snow observations are taken daily for climate and weather recording purposes. They provide relatively high temporal, spatial, and elevational resolution on event-scale processes. Each day starts with no snow and records only new snowfall (*ie*, no memory of prior conditions). Ratios of cooperative snow depth to liquid equivalent precipitation apply only to events at single-day resolution. Most observers are volunteers, and observations can be erratic, so each station must be evaluated individually prior to use.

Snowcourse survey measurements are used to gage the water supply. These observations are taken by trained personnel, most of whom work for water controlling or using agencies. These agencies include the

California Department of Water Resources, the US Forest Service, public utilities, and private land companies or irrigation districts. Surveys are conducted one to six times each wet season (December through May), depending on the needs and resources of the controlling agency. The most common dates are on or near the first of the month in February and April. Since they are usually sampled only once per month, snowcourses have low temporal resolution. Although they lack event-scale information, snowcourses integrate conditions throughout the snowpack accumulation/ablation season and are the primary measure of the water supply contained in the snowpack. Ratios of snowcourse depth to water content provide an index of seasonal-scale conditions (Cayan *et al* this volume).

Snow and Liquid Equivalent Precipitation

We computed daily mean snow measurements for Lake Spaulding for 1949 to 1989. Means, means plus one standard deviation, and maxima are shown in Figure 3. There is considerable variation throughout the wet season, with little more likelihood of large events in the early season (day 62 or December 1) than the late season (day 182 or March 31). Lake Spaulding's mean monthly snow accumulation is compared to that of precipitation in Figure 4. Means, means plus/minus one standard deviation, minima, and maxima are graphed over the water year for both variables. While snow accumulation lags about a month behind precipitation at the beginning of the wet season, it decreases and ends about the same time as precipitation in the latter part of the wet season. In the 1949-1989 wet seasons (November 1 through March 31), Lake Spaulding had 7,401 observations where both precipitation and snow values were present. There were 2,528 days with precipitation and 1,565 days with snow, so about 34% of the days had precipitation and about 62% of those had snow.

In terms of 1949-1989 mean monthly precipitation divided by number of days per month, Lake Spaulding received a symmetric 8 mm of liquid equivalent per day during both November and March and 10 mm per day during December, January, and February. Snow is much more complicated. Lake Spaulding received less snow in November (20 mm per day) than it did in April (25 mm per day), a month with less than 60% of November's precipitation. The accumulated snow depth had a bimodal peak, with maxima in January (44 mm per day) and March (42 mm). February shows a distinct decline (39 mm). January and March are the only months that never had zero snow accumulation. The January snow peak coincides with the wet season precipitation peak. The March peak is probably a function of mean storm temperature, with late season storms being colder than those earlier in the season (Lee 1987; Minnich 1986).

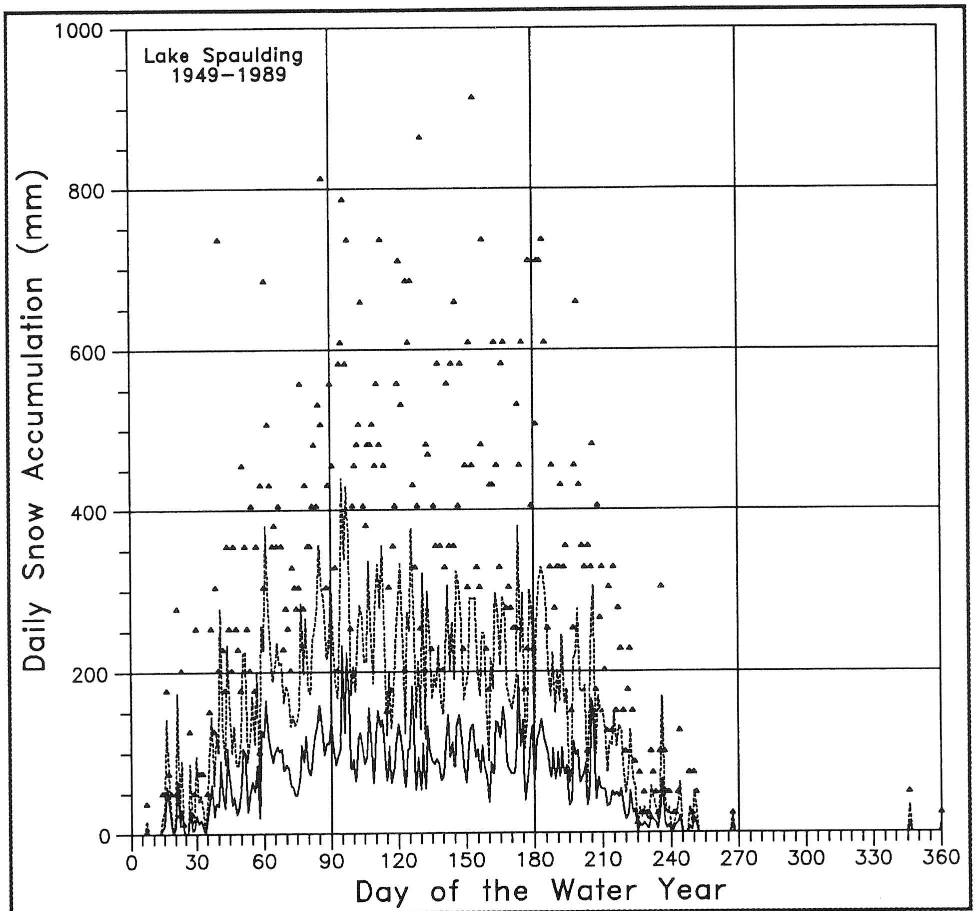


Figure 3. Daily means (solid line), means plus one standard deviation (dashed line), and maxima (closed triangles) snow accumulation at the Lake Spaulding cooperative station.

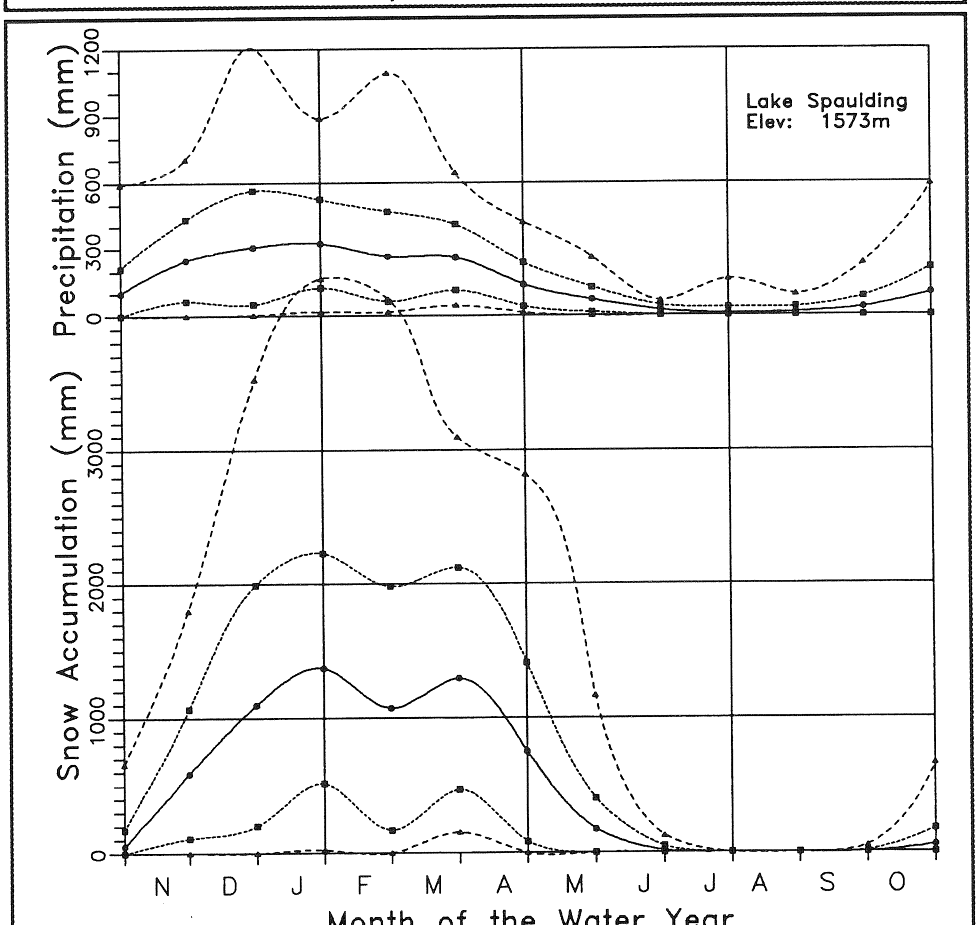


Figure 4. Monthly climatological statistics for the Lake Spaulding cooperative station for precipitation and snow accumulation based on 1949-1989 data. The center solid curved lines are long-term means. The dotted lines to either side of the means are means +/– one standard deviation. The outer dashed lines are maxima and minima. The curves are cubic splines of monthly data.

A comparison of time series of Lake Spaulding's water year snow and precipitation is presented in Figure 5. The 9-year Gaussian-filtered values (closed circles) show a high degree of similarity, but individual yearly values can diverge significantly. The snow peaks at 1952, 1967, 1969, and 1982 (the four highest snow years in this record) coincide with precipitation peaks, but the snow peak in 1979 is a precipitation low while the snow low in 1970 corresponds to a precipitation value that is above normal. These differences illustrate that snow and liquid equivalent precipitation can capture significantly different aspects of climate variability, even though they are generally closely related.

We originally intended to use the Bowman Dam cooperative record for the Yuba River. A close examination of the record at Bowman Dam exhibited a strong correlation with surrounding stations at monthly and annual time scales, but a distinct lack of correlation at a daily scale. We believe this may be due to observational practices that are inconsistent with neighboring stations. This underscores the need to examine each cooperative station before use.

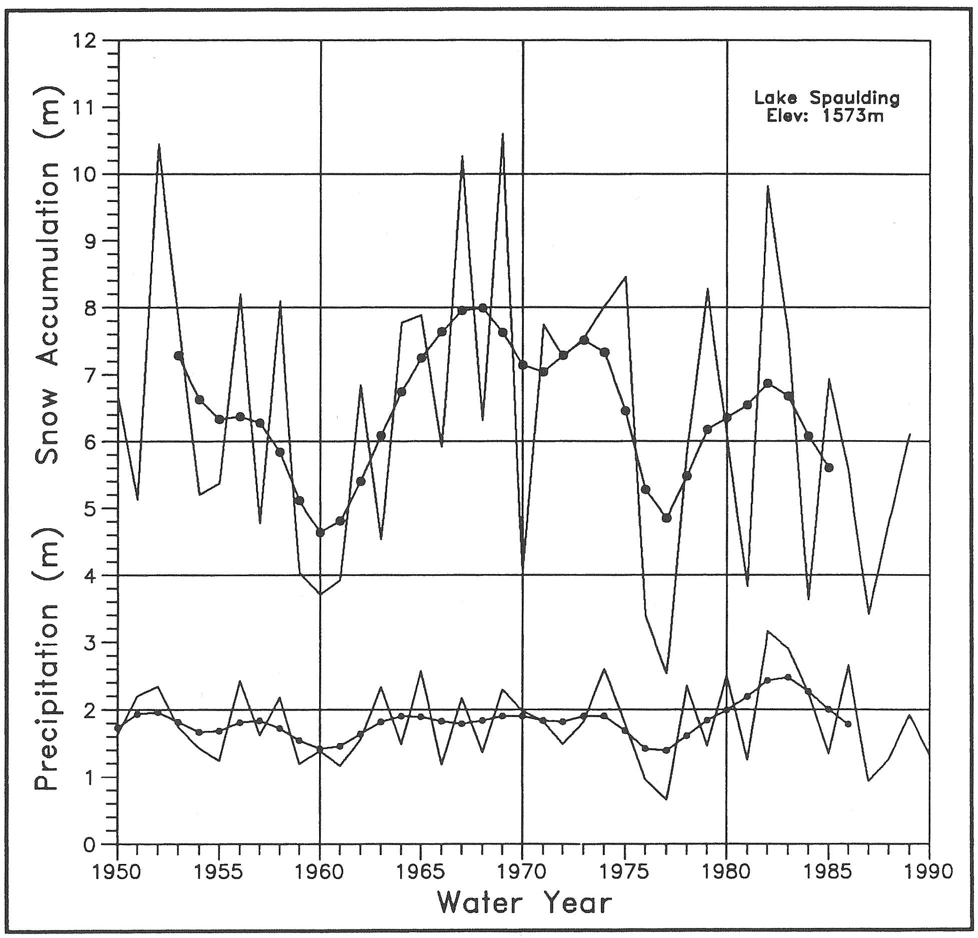


Figure 5. The water year (October 1 through September 30) snow accumulation and precipitation at Lake Spaulding. The correlation coefficient for liquid equivalent precipitation vs. snow accumulation is 0.56. The line connecting the closed circles is the Gaussian 9-year low pass filtered values.

Snow Depth vs. Snow Water Content

A comparison of the time series of the January/February snow accumulation at the cooperative snow stations (Figure 6) and the April 1 readings at the nearby snowcourses (Figure 7) exhibit strong similarities between the monthly and longer scale variability occurring for the two snow parameters.

In-basin correlations between cooperative station and snowcourse values are reasonably high considering the differences mentioned above ("Monthly" in Table 2). When the cooperative values are correlated with month-to-month changes in the snowcourses (the "change in WC" entries in Table 2), the coefficients improve significantly. The highest coefficients overall are exhibited between the cooperative station seasonal accumulations and the snowcourse readings ("Accumulations" in Table 2). This is achieved by comparing the January snowcourse readings with the December cooperative snow accumulation, the February snowcourse with the December plus January cooperative snow, March snowcourse with December through February cooperative snow, and so on.

Table 2
Correlation Coefficients for Each Snowcourse and Associated Cooperative Station

Donner Summit	Jan	Feb	Mar	Apr	May
Lake Spaulding					
Monthly	.51	.48	.51	.32	.59
δWC	.38	.68	.54	.81	--
Accumulation	.66	.76	.75	.73	.74
Kaiser Pass	**Jan**	**Feb**	**Mar**	**Apr**	**May**
Huntington Lake					
Monthly	.47	.53	.57	.37	.40
δWC	.60	.75	.59	.60	--
Accumulation	.54	.72	.80	.75	.91

Monthly = Snow course 1st day of the month water content reading vs. the previous month cooperative snow depth accumulation.
δWC = Snow course monthly change in water content vs. monthly cooperative snow depth accumulation.
Accumulation = Snow course 1st day of the month water content reading vs. the sum of the cooperative snow depth previous months snow accumulation.

There is also significant correspondence between snow variability in the two Sierra basins. The San Joaquin normally receives slightly less snow than the Yuba, although it is at higher elevation. Previous research has demonstrated that the snowcourse anomalies exhibit a high degree of coherency throughout the Sierra Nevada (*eg*, Aguado 1990). Correlation coefficients for the monthly values at each station (Table 3) also show a strong relationship across the 250 kilometers separating the basins. Correlation coefficients for monthly snowcourse measures never fall below 0.8 for the months from January through May. We next examine the validity of using the cooperative snow records to examine event-scale phenomena that may be muted at monthly and seasonal time scales. One such parameter is the snow ratio, the ratio of daily snow accumulation to daily liquid equivalent.

Table 3
Correlation Coefficients for Monthly Snowcourse Water Content Values for Donner Summit vs. Kaiser Pass and Cooperative Snow Depth for Lake Spaulding vs. Huntington Lake

Station Type	Jan	Feb	Mar	Apr	May
Snow Course WC	.82	.85	.87	.83	.81
Coop Snow Depth	.64	.76	.68	.76	.49

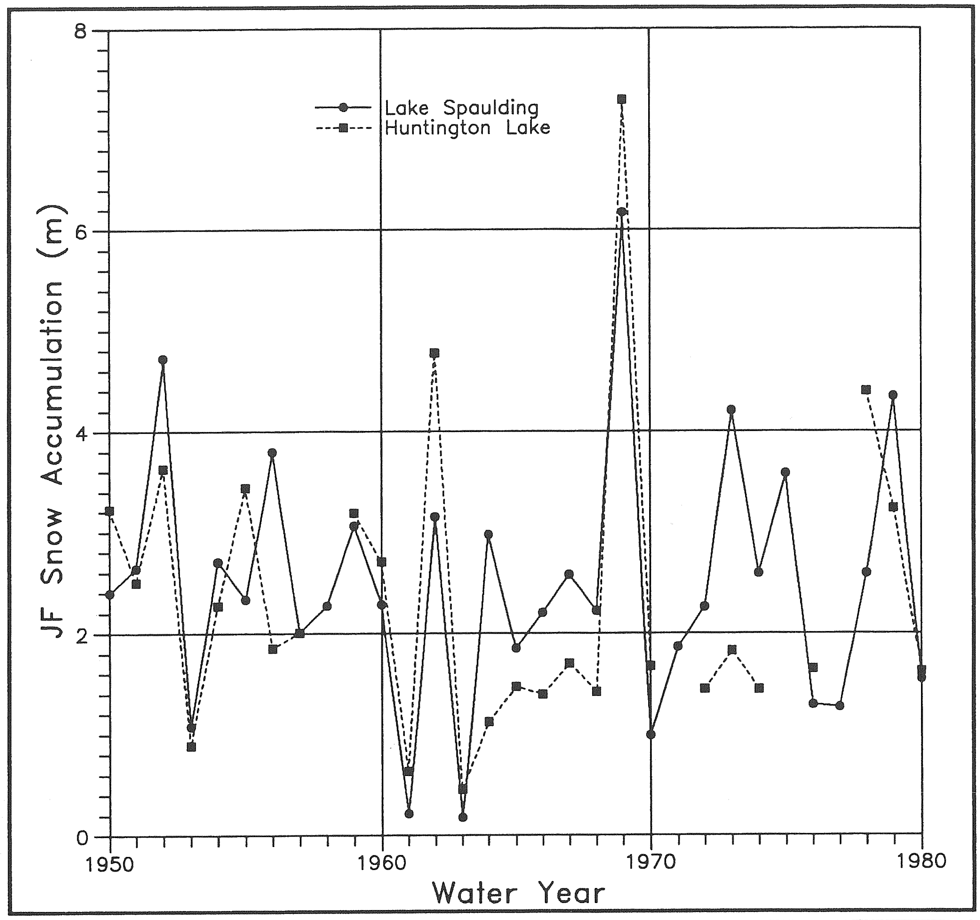


Figure 6. The January/February snow accumulation at Lake Spaulding and Huntington Lake cooperative stations. The correlation coefficient for Lake Spaulding vs. Huntington Lake is 0.70. The graph is limited to January and February to minimize problems with missing data at Huntington Lake, which is particularly spotty in the 1970s and 1980s.

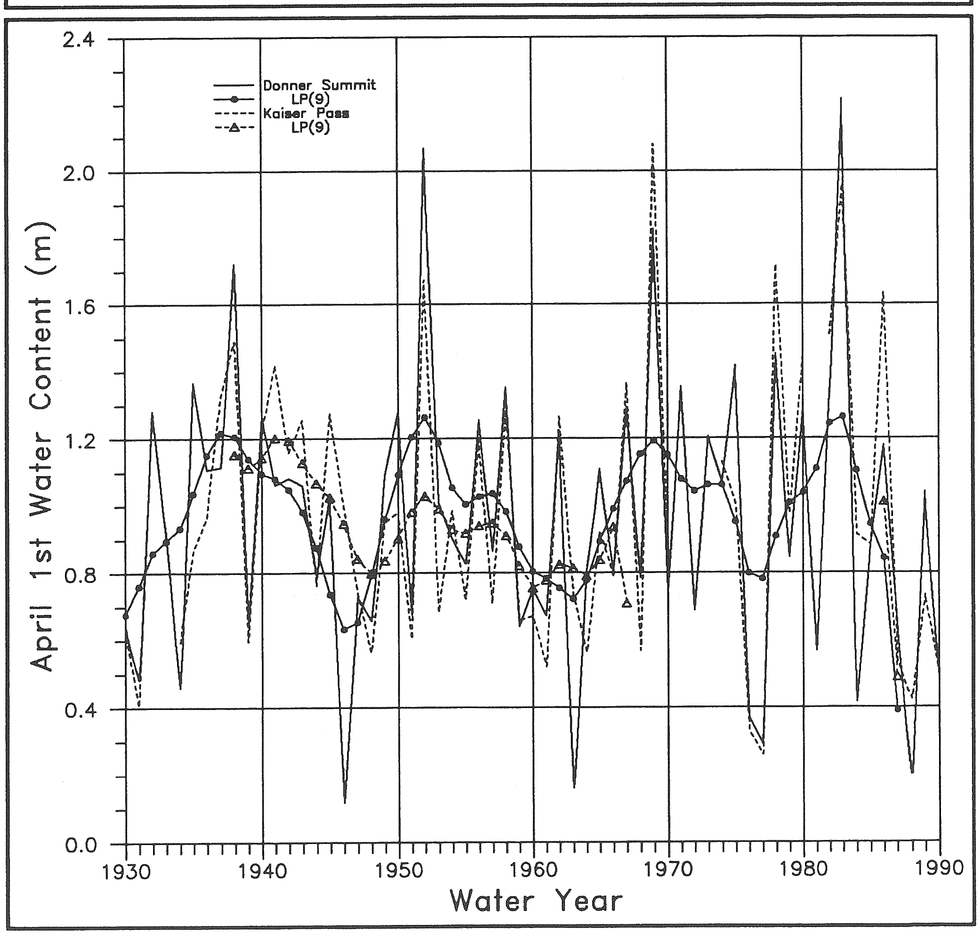


Figure 7. The April 1 snow water content measurements at Donner Summit and Kaiser Pass snowcourses. The correlation coefficient is 0.83. The triangles indicate the Gaussian 9-year low pass filtered values. Kaiser Pass has missing data in the 1970s and 1980s.

The Snow Ratio: Dry Snow vs. Wet Snow

The snow ratio is a measure of the dryness of snow. It is computed by dividing snow accumulation by liquid equivalent precipitation. It is more robust than computing density of snow (liquid equivalent over snow). It is possible to have precipitation without snow but impossible to have snow without precipitation. The former results in a snow density that is undefined, but a snow ratio of zero.

Since we were interested in behavior associated with snow conditions, we selected all days at Lake Spaulding with snow accumulations greater than zero. We divided all those days into four liquid equivalent precipitation categories: light (1 to 4 mm), moderate (5 to 25 mm), heavy (26 to 50 mm), and intense (greater than 50 mm). We then selected the 25 highest and 25 lowest snow ratio days for each category and composited the 700-mb heights, surface to 700-mb layer temperature anomalies, and height anomalies. The light and intense category composites are presented in Figures 8 and 9. It is interesting to note that light precipitation, whether high or low ratio, is associated with low heights near 120W and high heights near 150W and with westerly to northwesterly flow over Lake Spaulding. The main differences are that high snow ratio/light precipitation (HL) days had ridging at 140W, higher highs and lower lows than the low ratio/light precipitation (LL) days, and a significant layer temperature anomaly field in the eastern North Pacific. The moderate and heavy precipitation composites (not shown) exhibit a smooth transition to the intense precipitation composites. The similarities in high and low ratio intense precipitation are southwesterly flow over Lake Spaulding and a deep height anomaly offshore. The high ratio/intense (HI) positive height anomaly is similar in location and intensity to HL, but the low is deeper and farther west. The associated temperature anomaly has also moved west. The low ratio/intense (LI) composite negative height anomaly has also moved offshore and deepened but is still not as intense as HI. The positive height anomaly has moved north into Alaska. The layer temperature anomaly field, while better organized, is still fairly flat. The dominant feature exhibited by the composites is the meridional flow (and associated height and temperature anomalies) found with high ratio snow. Low ratio snow is found during periods of zonal flow.

A comparison of Lake Spaulding liquid equivalent precipitation and temperature recorded during the composited days described above is given in Table 4. We computed means for precipitation and temperature for the eight categories mentioned above. High ratio (dry) snow is associated with cooler temperatures and lighter precipitation. Differences in mean temperature range from 1.4 to 5.2°C between the low and high ratios of the four precipitation classes. However, the temperature behavior is more complicated when minimum and maximum temperatures are examined. In both snow ratio groups, temperature minima vary similarly: as precipitation intensity increases, minimum temperatures increase. Maxima vary inversely: as precipitation intensity increases, high ratio

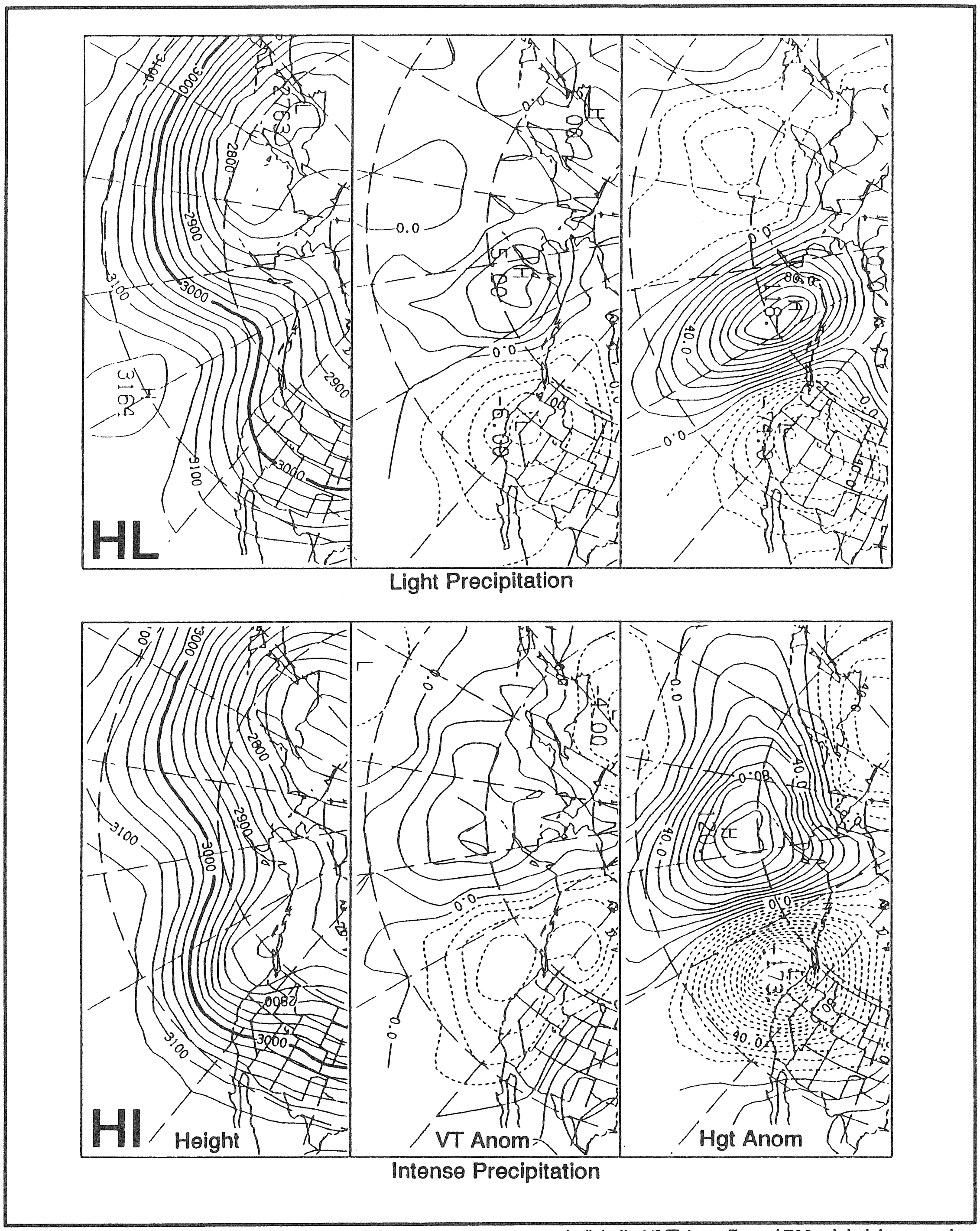


Figure 8. 700-mb height, sea surface to 700-mb layer temperature anomaly (labelled "VT Anom"), and 700-mb height anomaly composites of the low snow ratio light and intense precipitation days.

temperature maxima decrease and low ratio temperature maxima increase. The similar temperature minima patterns are probably related to increasing cloud cover and decreased outgoing longwave radiation. The dissimilar temperature maxima patterns are probably related to the source regions of the air masses ("warm" vs. "cool" storms). The lowest snow ratios occurred with the heaviest precipitation. Also, the precipitation in each low ratio group is consistently higher than that of the corresponding high ratio group.

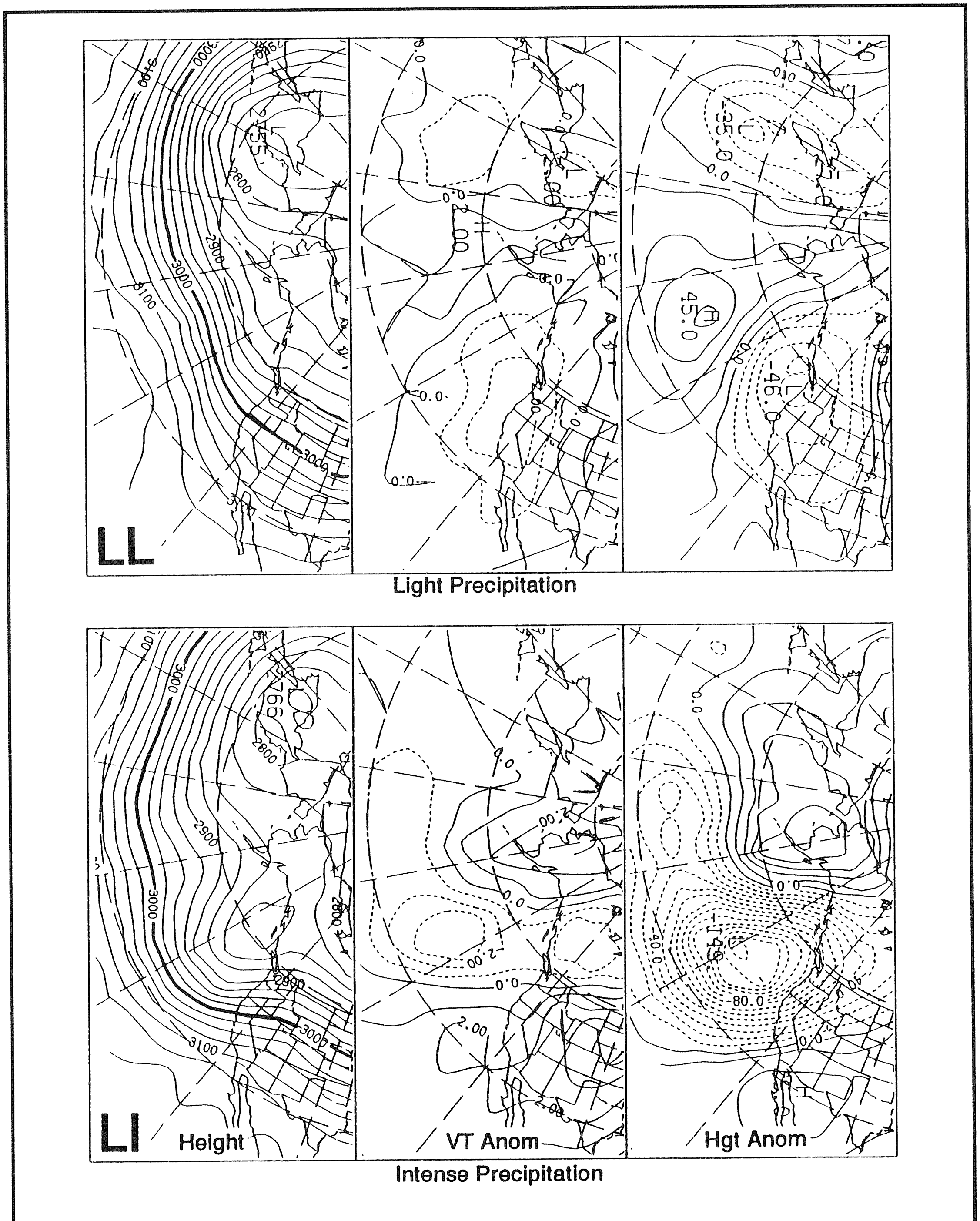


Figure 9. 700-mb height, sea surface to 700-mb layer temperature anomaly (labelled "VT Anom"), and 700-mb height anomaly composites of the high snow ratio light and intense precipitation days.

Table 4
Mean Precipitation and Temperature Values for Lake Spaulding for the 25 Days in Each of the Eight Precipitation/Snow Ratio Categories (4 Precipitation Categories by 2 Snow Ratio Categories) Used in the Study

Category	Precipitation (mm) Ppt	Snow	Ratio	Temperature (C) Max	Mean	Min
High Ratio						
01 - 04mm	1.7	47.6	28.2	5.2	-1.1	-7.4
05 - 25mm	10.0	177.4	18.1	2.0	-2.6	-7.1
26 - 50mm	35.2	463.4	13.1	0.6	-1.7	-4.1
> 50mm	64.2	642.1	10.0	0.0	-2.1	-4.2
Low Ratio						
01 - 04mm	3.8	19.9	5.2	4.8	0.3	-4.3
05 - 25mm	20.1	17.1	0.8	5.6	1.8	-2.0
26 - 50mm	39.5	21.2	0.5	5.4	2.4	-0.5
> 50mm	99.4	21.8	0.2	6.2	3.1	0.0

Ppt = Mean Category Daily Precipitation
Snow = Mean Category Daily Snow Accumulation
Ratio = Mean Category Daily Snow Ratio (Snow/Ppt)

Summary and Conclusions

We examined two measures of snow, cooperative daily snow accumulations and snowcourses, at two widely separated locations in the Sierra Nevada of California. There is considerable spatial coherence in the monthly anomalies of both snow measures.

Cooperative station records must be used with caution, since observation practices vary from station to station and year to year. However, since with over 400 active cooperative stations in California at elevations above 500 meters, it is not difficult to locate a usable station below 1500 meters. The choice of stations above 1500 m is limited.

Cooperative snow depth measurements provide details of winter precipitation during storm events. When combined with station liquid equivalent precipitation, they produce the snow ratios (snow depth to liquid water equivalent) whose data yield information on cool vs. warm storms (or dry vs. wet snow events). The cooperative stations also provide data for the temperature sensitive mid-elevation basin zones that are poorly sampled by snowcourses.

Climatological information extracted from cooperative snow depth records shows seasonal accumulation of snow depth at cooperative stations is related to water content at nearby snowcourses (correlation coefficients are mostly above 0.7). Wet season snow frequency is closely correlated with precipitation frequency; 61% of all wet season precipitation days at Lake Spaulding also recorded snow.

Two snowcourses, Donner Summit (Yuba River basin) and Kaiser Pass (San Joaquin River basin), exhibit similar variability even though they are

250 kilometers apart in space and over 600 meters in elevation. We also showed a strong correlation between the individual snowcourse records and nearby cooperative snow depth records.

An interesting portrait of snowstorm patterns is provided by extreme cases of snow ratio and precipitation intensities. This portrait demonstrates a remarkable contrast in atmospheric circulation pattern and regional temperature for high vs. low snow ratio events. This is provided by composites of 700-mb height and temperature values. High snow ratios are produced by strong ridging near 150W, inducing strong meridional flow just offshore. Low snow ratios are related to pronounced zonal flow that extends from the eastern North Pacific near 30N-35N. These patterns intensify as total precipitation increases in these high or low snow ratio events.

Combined with precipitation and nearby snowcourse water content records, cooperative snow records appear to be a useful resource for both synoptic and climatic studies. Many cooperative snow records are available in computer readable form as far back as 1948. Longer records are available on paper copies, and will likely be digitized as their utility is recognized.

Acknowledgments

LGR and DRC acknowledge support by the University of California, Water Resources Center, Project UCAL-WRC-W-768, and by the NOAA Experimental Climate Forecast Center. Funding for DRC was also provided by the US Geological Survey via an Intergovernmental Personnel Act agreement with the University of California.

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